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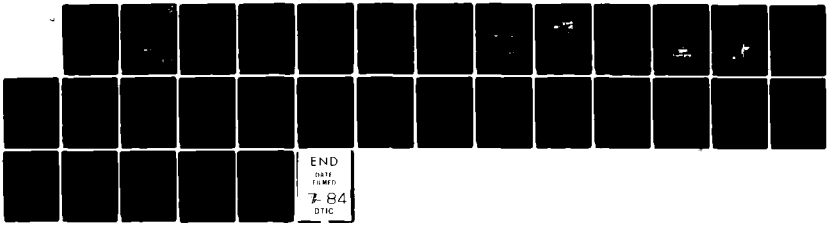

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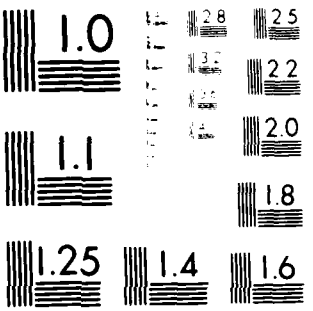
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NWC TP 6508

Analysis of Particulates in the Exhaust Plume of a TF30 Engine at Military Power

by
Larry A. Mathews
Carl A. Heller
Joseph H. Johnson
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MAY 1984

NAVAL WEAPONS CENTER
CHINA LAKE, CALIFORNIA 93555

Naval Weapons Center
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FOREWORD

Particulate matter (smoke) in the exhaust plumes of military aircraft is a highly visible pollutant which has resulted in frequent complaints from the public. The results from work described in this report will be combined with results obtained at the North Island Naval Air Station, San Diego, California, to develop an understanding of particle growth in the aircraft exhaust plume. Such an understanding should enable the Navy to engineer solutions to reduce the quantities of particulate matter released to the environment by military aircraft engines.

This report describes work performed at the Naval Weapons Center during fiscal year 1983. The work was performed using Pollution Abatement Research funds, Program Element Number 62765N, NAVAIR Task Area Numbers F65559 under the sponsorship of A. F. Klarman.

This report was reviewed for technical accuracy by R. L. Derr, A. R. Kelso, and K. J. Krautle.

Approved by
E. B. ROYCE, Head
Research Department
15 April 1984

Under authority of
K. A. DICKERSON
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(U) This report presents particulate concentration, emission index and size distribution data in the plume of a TF30-P1 engine, run at military power in the open air. The particle size distribution data measured here show that the mass median aerodynamic diameter of the particles is in the range of 0.19-0.30 micrometer compared to an average of 0.18 micrometer for the test cell data for a rebuilt TF30-P414 engine. Recommendations are listed for future tests.

CONTENTS

INTRODUCTION

The analysis of particulates in the exhaust plume from jet engines is one project in a large program to study the pollution caused by military aircraft. Sampling high power jet engine exhaust for pollutants is difficult, and several techniques are being employed to obtain a realistic picture. Also, the reduction in visibility due to particulate emissions is of considerable interest.

In the analytical method currently in use in industry, particulate sampling is conducted over the exhaust exit plane of a jet engine test cell stack (Reference 1 and 2). Although the stack temperature may exceed 150°C at the sampling point, the total mass of particulate per sample volume at ambient temperature (20°C) can be obtained. This is accomplished by drawing the stack gas through a heated glass fiber filter (maintained at a temperature of 120°C), and then by drawing the stack gas through an ice cooled impinger train (maintained at a temperature of 20°C). Particulates that would exist at ambient temperature include the solids collected at 120°C and those collected as condensable matter at 20°C. This measurement is repeated at a matrix of sampling points throughout the cross section of the stack. Appropriate calculations yield an emission index (EI).

Particle size distribution data, taken from a test cell stack, may not be representative of the exhaust aerosol that is allowed to grow in the open air. In the open air, entrainment of atmospheric air causes rapid cooling of the exhaust plume. The particles grow due to condensation of hydrocarbon from the gaseous stream as the temperature decreases in addition to the normal particle growth from collision.

The objective of our work was to sample and analyze the plume of a military jet engine in the open air to determine the particle size distribution and total particulate concentration. Gas samples were collected for monitoring combustion gases and for calculating quantities of fuel consumed. These data were then to be compared to those taken in test cells where samples were collected at temperatures above 150°C. Eventually, these data will supplement particle size distribution measurements made by new optical methods being developed by the University of Tennessee Space Institute, Tullahoma, Tennessee, as part of the program of the Naval Air Propulsion Center, Trenton, New Jersey.

Pollution abatement work is underway at the Naval Weapons Center (NWC) to understand the pollutants produced by ordnance. This analyti-

cal technology has been adapted to study the exhaust of Navy aircraft. In this report, a preliminary study of particulate concentration, size distribution, and fixed gases in the exhaust of a TF30-P1 engine is presented. A refinement of sampling technique, based mostly on this preliminary work, is proposed for future studies.

EXPERIMENTAL

The open air Weapons Survivability Laboratory site at NWC was used for the tests. An F-111 aircraft with a TF30-P1 engine, a prototype TF30 engine which has been used extensively since the late 1950s, was mounted so that the center of the exhaust port was approximately 1.8 meters above the ground (Figure 1). The ground was covered with a concrete pad and a steel sheet extending several hundred feet behind the engine. Sampling equipment was placed behind barricades on a platform in the exhaust plume as shown in Figure 2.

FIGURE 1. Side View of F-111 Aircraft Positioned on Test Pad.

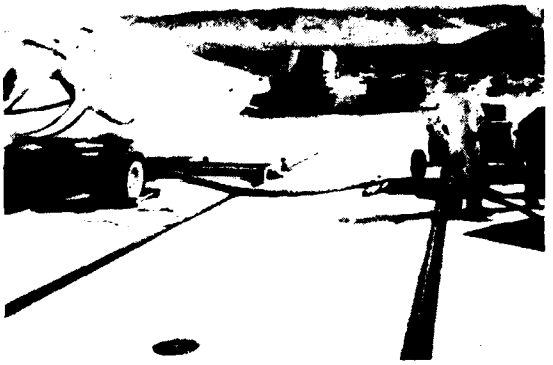
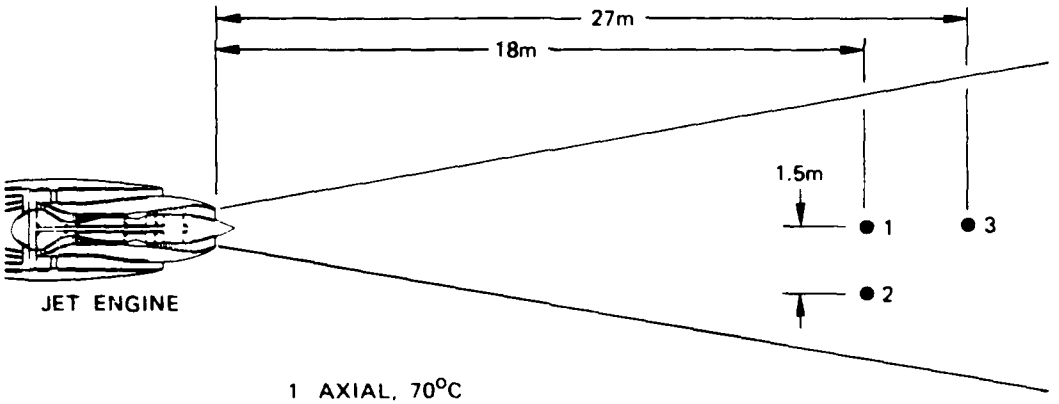


FIGURE 2. Aircraft and Sampling Equipment.

LOCATION OF SAMPLING POINTS

Particulate samples were obtained at 70 and 50°C in order to observe particulate growth with a decrease in temperature. At temperatures above 70°C, the flow velocity of the plume affected the stability of the sampling station. In addition, high temperatures were detrimental to the sampling equipment. Ideally, temperatures below 55°C were best for sampling particulates because most volatile hydrocarbons are gases above this temperature.

While the engine was run at military power, temperature probing was used to locate 70 and 50°C axial, and 50°C off axis sampling points (Figure 3). These locations exhibited stable temperatures (±5°C) and little drift with time after engine warmup. The velocity of the plume was 90, 48, and 70 m/s at sampling points 1, 2, and 3, respectively. Both particulate sampling and temperature probing were conducted on days of low wind velocity in order to minimize changes in the plume trajectory.



1 AXIAL, 70°C
2 OFF AXIS, 50°C
3 AXIAL, 50°C

FIGURE 3. Location of Sampling Points With Temperatures of 50 and 70°C as Viewed From Above.

SAMPLING APPARATUS

Gas Sampling Apparatus

A gas sampling system was designed and built to collect eight gas samples, in pairs, sequentially (The schematic is shown in Figure 4).

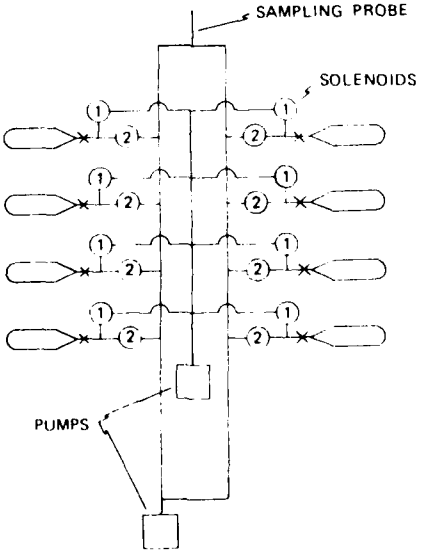


FIGURE 4. Schematic of Gas Sampling Apparatus.

In this figure, the pump solenoids are labeled 1 and the sample solenoids are labeled 2. Prior to the test, the pump solenoids were opened to evacuate the flask. During the test, the pump solenoids were closed and the sample solenoids were opened for 10 seconds to collect each gas sample. After sampling, both solenoids were closed to isolate the gas sample. When it was safe to approach the sampling system, the manual valve on the sample flasks were closed. The sample flasks were then removed from the sampling system and transported to the laboratory for analysis.

Particle Sampling Apparatus

Two different types of sampling apparatus were utilized. One of them served to make total particle collections. It consisted of a 100 millimeter diameter, type A, glass fiber filter contained in a Sierra model 710 stainless steel, filter housing. The other collectors were particle size analyzers; an Anderson 14-Stage Low Pressure Impactor (LPI) and a Sierra Three-Stage In Stack Inhalable Particulates Cyclone Sampler. The particle collectors and pumps were mounted to the platform behind the shielding barricade. This set up is shown in Figure 5. The particle laden air was drawn to each particle collector through stainless steel probes about 2.5 meters in length and 1.3 centimeters

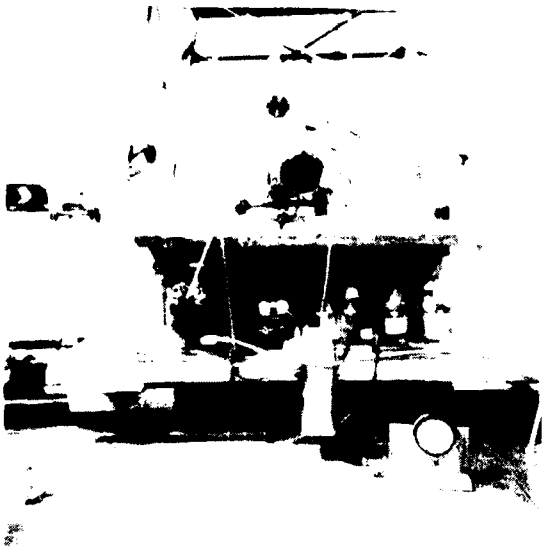


FIGURE 5. Particle Sampling Apparatus Located Behind Protective Shield. The jet engine exhaust port can be seen in the background just above the protective shield.

inner diameter. Isokinetic nozzles were placed on the end of each probe facing into the plume (Figure 6). The intake probes were located on the platform approximately 1.8 meters above ground level and were located away from surfaces that might cause flow stagnation. The flow rates through the LPI and cyclone sampler were 3 L/m and 18 L/m, respectively for all the tests. The average flow rate through the 100 millimeter diameter filter used to capture a total particulate sample was 59.5, 68.0, and 71.0 L/m at sampling points 1, 2, and 3, respectively.

Particle Size Distribution Measurement

Initially, particle size distributions were to be determined by both an Anderson 14-Stage Low Pressure Impactor (LPI) and a Sierra Three-Stage In Stack Inhalable Particulates Cyclone Sampler. However, the cyclone sampler was unsatisfactory for determining size distribution because of the short sampling time and the small amount of particulate sampled. The particulate had to be transferred from the collection cups of the cyclone sampler; a source of significant error for small quantities of particulate.

The LPI captured particles by inertial impaction on individual fiberglass substrates for particle diameter ranges >35.0, 21.7-35.0, 15.7-21.7, 10.5-15.7, 6.6-10.5, 3.3-6.6, 2.0-3.3, 1.4-2.0, 0.90-1.4, 0.52-0.90, 0.23-0.52, 0.11-0.23, 0.08-0.11, and <0.08 micrometers. Small quantities of particulate matter were detected on each substrate by difference weighing.

FIGURE 6. Isokinetic Probes Facing Into the Plume Which is Flowing From Left to Right in the Photograph.

SAMPLING TECHNIQUE

Tests with the engine at military power were made at each of the three sampling points to determine the concentration and size distribution of particulates. The sampling time for each run was 10 minutes. The jet engine was run for 5 minutes prior to sampling to allow the engine to stabilize.

All filters and substrates were desiccated and weighed prior to, and after, sampling to determine the mass of particulate collected. The filters and substrates were stored in large petri dishes prior to and after sampling.

DATA PRESENTATION

PARTICLE SIZE DISTRIBUTIONS

The mass of particulate collected for each size range was determined to be the difference between the tare and final weights for each glass fiber substrate used in the Anderson 14-stage LPI. Thus, the mass percent of particulate in each size range was found. These data are contained in Tables 1-3 and plotted as bar graphs in Figures 7-9.

TOTAL PARTICULATE CONCENTRATIONS

The total mass of particulate collected was determined to be the difference between the tare and final weights of the 100 millimeter glass fiber filter. The filters yielded significant quantities of particulates; i.e., 50.9, 37.9, and 44.5 mg for points 1, 2, and 3, respectively. The total concentrations at points 1, 2, and 3 were calculated to be 86.3, 55.7, and 62.7 mg/m^3, respectively.

FIXED GASES

Samples collected for fixed gas analysis were analyzed using a Carle 8501 gas chromatograph with Porapak-N and Molecular Sieves 5A columns and a thermal conductivity detector. In this manner, we could monitor concentrations of H, CH_4, C_2H_6, C_2H_4, C_3H_8, C_3H_6, N_2, O_2, CO_2, and CO as low as 0.01%. The only contaminant found in these samples was CO_2. Concentrations of CO_2 found are listed in Table 4. This CO_2 data was used to approximate the quantity of fuel which had been burned to produce the particulates which we collected at each position.

TABLE 1. Anderson 14-Stage LPI Mass Size Distribution Data for the Test Made at Sampling Point 1.

Stage	Tare weight (mg)	Final weight (mg)	Mass collected (mg)	% Found in size range	Size range (μm)
0	657.5	657.5	0.0	0.0	>35.0
1	714.9	714.9	0.0	0.0	21.7-35.0
2	678.2	678.4	0.2	5.9	15.7-21.7
3	790.7	790.8	0.1	2.9	10.5-15.7
4	720.3	720.3	0.0	0.0	6.6-10.5
5	648.4	648.4	0.0	0.0	3.3-6.6
6	726.2	726.2	0.0	0.0	2.0-3.3
7	781.8	781.9	0.1	2.9	1.4-2.0
LP1	712.9	713.0	0.1	2.9	0.90-1.4
LP2	725.6	725.9	0.3	8.8	0.52-0.90
LP3	650.0	650.7	0.7	20.6	0.23-0.52
LP4	652.9	654.0	1.1	32.4	0.11-0.23
LP5	665.8	666.4	0.6	17.6	0.08-0.11
Final Filter	699.4	699.6	0.2	5.9	<0.08
TOTAL MASS COLLECTED			3.4 mg	99.9	

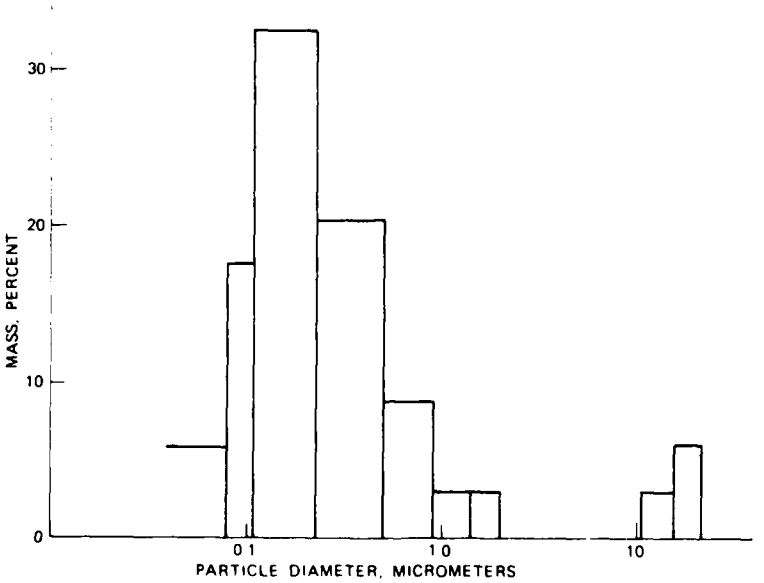


FIGURE 7. Mass Percent Versus Particle Diameter for the Test at Sampling Point 1.

TABLE 2. Anderson 14-Stage LPI Mass Size Distribution Data for the Test Made at Sampling Point 2.

Stage	Tare weight (mg)	Final weight (mg)	Mass collected (mg)	% Found in size range	Size range (μm)
0	654.1	654.1	0.0	0.0	>35.0
1	657.5	657.5	0.2	8.7	21.7-35.0
2	703.4	703.5	0.1	4.35	15.7-21.7
3	715.3	715.4	0.1	4.35	10.5-15.7
4	763.8	763.8	0.0	0.0	6.6-10.5
5	638.1	638.1	0.0	0.0	3.3-6.6
6	640.1	640.1	0.0	0.0	2.0-3.3
7	718.7	718.8	0.1	4.35	1.4-2.0
LP1	718.7	718.8	0.1	4.35	0.90-1.40
LP2	765.6	765.9	0.3	13.0	0.52-0.90
LP3	641.6	642.2	0.6	26.1	0.23-0.52
LP4	716.1	716.6	0.5	21.7	0.11-0.23
LP5	299.5	299.7	0.2	8.7	0.08-0.11
Final Filter	707.7	707.8	0.1	4.35	<0.08
TOTAL MASS COLLECTED			2.3	99.95	

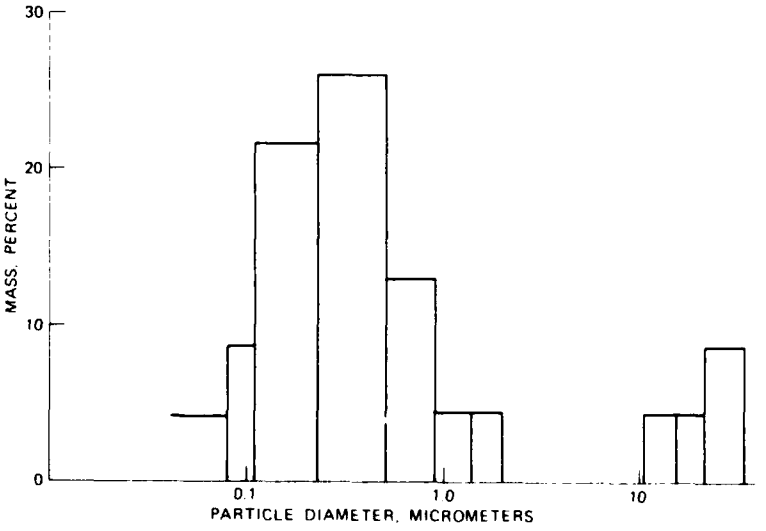


FIGURE 8. Mass Percent Versus Particle Diameter for the Test at Sampling Point 2.

TABLE 3. Anderson 14-Stage LPI Mass Size Distribution Data for the Test Made at Sampling Point 3.

Stage	Tare weight (mg)	Final weight (mg)	Mass collected (mg)	% Found in size range	Size range (μm)
0	697.3	697.3	0.0	0.0	>35.0
1	651.8	651.9	0.1	3.85	21.7-35.6
2	686.7	686.8	0.1	3.85	15.7-21.7
3	684.0	684.0	0.0	0.0	10.5-15.7
4	746.7	746.7	0.0	0.0	6.6-10.5
5	666.0	666.0	0.0	0.0	3.3-6.6
6	696.7	696.7	0.0	0.0	2.0-3.3
7	724.6	724.7	0.1	3.85	1.4-2.0
LP1	684.1	684.2	0.1	3.85	0.90-1.4
LP2	677.0	677.3	0.3	11.5	0.52-0.90
LP3	657.0	657.8	0.8	30.8	0.23-0.52
LP4	693.8	694.5	0.7	26.9	0.11-0.23
LP5	727.9	728.2	0.3	11.5	0.08-0.11
Final Filter	650.9	651.0	0.1	3.85	<0.08
TOTAL MASS COLLECTED			2.6	99.95	

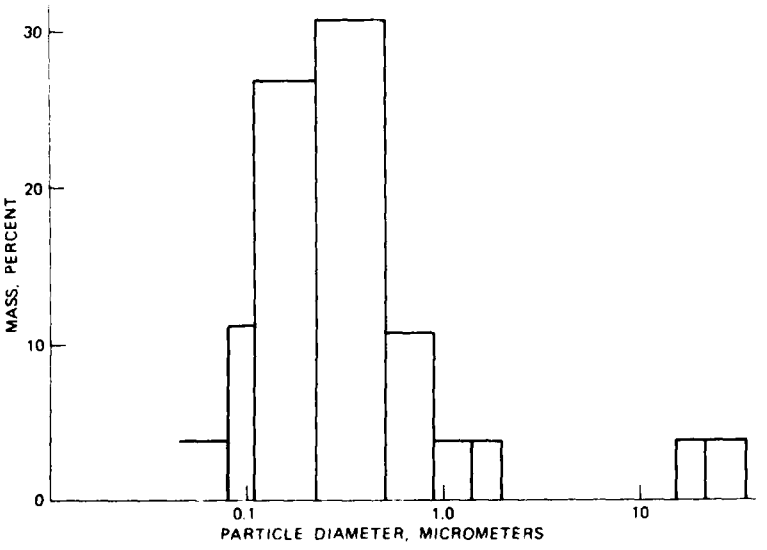


FIGURE 9. Mass Percent Versus Particle Diameter for the Test at Sampling Point 3.

TABLE 4. Gas Samples From TF30-P1 Jet Engine at Military Power.

Position	CO_2 Concentration (volume %)			
	2 Minutes	5 Minutes	8 Minutes	Average
1	0.29	0.27	0.28	0.28
2	0.17	0.17	0.19	0.18
3	0.18	0.18	0.19	0.18

DATA ANALYSIS AND DISCUSSION

Figures 7-9 indicate that with the engine running at military power most of the particulate mass was found in the 0.1-0.5 micrometer range. Very little mass was found for particle diameters from 1-10 micrometers in size. However, a detectable amount of particulate mass existed above 10 micrometers. These large particles were probably not associated with exhaust soot particles; rather, they may have been dislodged from the surfaces of the engine or the pad due to wind shear produced during the test. Particles with a high settling velocity may have adhered to the walls of the long sampling probes (2.5 centimeters), preventing their collection and subsequent detection on the filter substrate.

The mass median aerodynamic diameters for the above size distributions were 0.19, 0.30, and 0.27 micrometer for sampling points 1, 2, and 3, respectively, if the mass associated with particle diameters greater than 10 micrometers was excluded. These data imply a direct correlation of particle growth with a decrease in temperature. Size distribution data obtained in a test cell of the exhaust from a TP30-P414 at military power yielded 0.13 μm as a mass median diameter (Reference 3). If the soot particles were assumed to have a density of 2 g/c^3, the exhaust particles from the TF30-P414 would have had a 0.18 micrometer mass median aerodynamic diameter. Thus, increased particle growth may have occurred in the open air plume if the particulate does not contain other material such as fine dust.

The test stand vibrated at the high plume velocities, and some losses of particulate may have occurred due to vibration of the filter housing. This vibration could also have caused a skew in the particle size distribution data (from the Anderson LPI) because the larger particles would tend to fall from the upper stages and come to rest in the lower stages calibrated for smaller size ranges.

The particulate concentration decreased from 86.3 mg/m^3 at 70°C to 62.7 mg/m^3 at 50°C along the plume axis. This decrease was due to entrainment of ambient air and spreading of the plume with increased distance from the jet engine.

At 18 meters from the exhaust port, the average concentration over the cross section of the plume is about 42 mg/m^3, as calculated in Appendix A. For a rebuilt TF30-P414 engine run at military power in a test cell (Reference 2), the average concentration ranged from about 9-15 mg/m^3. The average concentration in the open air plume seems to be very high in comparison to the test cell data when one considers the higher air dilution in the plume of the TF30-P1 engine.

The particulate emissions index (EI) expressed as mass of particulates per 1,000 mass units of fuel consumed, was calculated from the CO_2 and only particulate data, as shown in Appendix B. The values of the EI calculated for each sampling point are shown in Table 5. These values might be lower if the calculation were to include uncondensed hydrocarbon gases which we did not monitor during the work (see Appendix B).

TABLE 5. Calculated Emission Indexes.

Sampling point	Distance from exhaust port, m	Temperature, °C	EI
1	18	70	61.1
2	18	50	59.5
3	27	50	64.1

As is evident from the table, there is no significant increase in EI with decreased temperature; however, the greater air dilution at points 2 and 3 compared to that of point 1 could mask any increase (see Appendix B) due to the condensation of hydrocarbons on particulate.

The measured values of EI are high compared to those reported for rebuilt TF30-P414 engines, run at military power, in test cells. Such rebuilt engines only produced emission indexes that ranged from 2.2-3.7 (Reference 2).

SUMMARY AND CONCLUSIONS

The open air plume test data for a TF30-P1 engine yielded concentration and emission index data that significantly exceeded the test

cell data for a rebuilt TF30-P414. Both engines were tested at military power. However, the TF30-P1 engine had seen extensive use since the late 1950s and had not been rebuilt. As a result, its high emissions may have been caused by poor tolerances in the engine. The emission indexes of 59.5-64.1 are about a factor of 6 higher than test cell data obtained from a rebuilt J79 engine run at military power. The J79 is considered to be the Navy's dirtiest engine (Reference 3). The emission index data were calculated from material balances of carbon dioxide and particulate matter; however, the above EI values would be smaller if uncondensed hydrocarbon gases were present and had been included in the calculations.

The particle size distribution data show that the mass median aerodynamic diameter of the soot particulate is in the range of 0.19-0.30 micrometer compared to an average diameter of 0.18 micrometer for test cell data. It is difficult to ascertain whether the particle growth is influenced by external contaminants, redispersion of particles which had previously adhered to engine surfaces, or condensation.

From the experiences with these preliminary tests, we have developed some recommendations for future tests.

1. To make a better comparison of the two methods (test cell and open air), engines currently in use by the Fleet on which test cell data have been collected should be tested by the open air method.

2. Total particulates, as well as velocity and temperature, should be sampled at 4 or more points in a cross section of the plume to obtain concentration and velocity profiles. Such information will allow a calculation of the degree of entrainment and, thus, the dilution effect on EI.

3. If total particulate data is desired, sampling should be done below 55°C to avoid loss of volatile compounds as recommended by the Environmental Protection Agency (EPA).

4. To avoid vibrations, particle collection equipment such as the Anderson LPI and filter housing should not be connected directly to the sample intake barricade stand. They should be shock mounted on the pavement to the rear of the stand. Sample line connections should be designed to avoid transmission of vibrations.

5. To compare gravimetric and optical techniques of particle measurement, tests should be performed concurrently.

6. A more sensitive detector should be used to detect CO and hydrocarbons.

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Appendix A

CALCULATION OF AVERAGE PARTICULATE CONCENTRATION IN PLUME CROSS SECTION

The average particulate concentration can be calculated for a cross section of the jet plume if the cross section is assumed to b circular and if the particulate concentration gradient is approximated by a Gaussian distribution. For a circular isothermal jet, the Gaussian representation (Reference 4) for the fully developed region is

$$\frac{\bar{C}}{\bar{C}_m} = \exp\left[-57.5\left(\frac{r}{x}^2\right)\right] \qquad \text{(A-1)}$$

where $\bar{C}$ is the time averaged concentration at distance r from the jet axis, and $\bar{C}_m$ is the time average centerline maximum concentration at the distance x downstream. Use of this equation, only roughly approximates the true conditions because the jet engine plume is not isothermal and it tends to have a buoyancy effect. Also, the lower part of the spreading plume comes in contact with the ground which distorts its circular cross section.

Because of the above considerations, a more general Gaussian distribution is

$$\frac{\bar{C}}{\bar{C}_m} = \exp\left[-A\left(\frac{r}{x}^2\right)\right] \qquad \text{(A-2)}$$

where A is a dimensionless constant.

Let C_{avg} be the average concentration over the cross sectional area of the plume and R be the radius of the plume. Also, the incremental area at radius r is $2\pi r\Delta r$. Thus,

$$\bar{C}_{avg}\ \pi R^2 = \int_0^R \bar{C}\ 2\pi r dr \qquad (A-3)$$

Substituting equation A-2 into equation A-3, rearranging and integrating gives

$$\bar{C}_{avg} = \frac{x^2 \bar{C}_m}{AR^2}\left[1-\exp\left[-A\left(\frac{R}{x}\right)^2\right]\right] \qquad (A-4)$$

Consider the experimental particulate concentrations at sampling points 1 and 2 at x = 18 meters. They are $\bar{C}_m$ = 86.3 mg/m^3 on the axis and $\bar{C}$ = 55.7 mg/m^3 at r = 5 feet. If these values are substituted in equation A-2, a value of 58.9 is found for A. The observed radius of the plume was estimated to be 3 meters at x = 18 meters. If the above values are substituted into equation A-4, $\bar{C}_{avg}$ is 41.8 mg/m^3 for this cross sectional point in the plume. This calculated average concentration may be either higher or lower due to deviations from the assumptions that the cross section of the plume is circular and the Gaussian distribution is applicable. Also, a significant error in the average concentration may occur if the radius of the plume was incorrectly estimated because the average concentration depends on the square of the radius.

Appendix B

EMISSION INDEX CALCULATION

The EI for particulates is defined as the mass of particulates emitted per 1,000 mass units of fuel consumed. An approximate EI can be calculated from the limited amount of data at a sampling point. The mass of carbon dioxide in the gas volume sampled for particulate is calculated, and the mass of fuel burned to produce that mass of carbon dioxide is found from a material balance of the assumed equation for combustion,

$$C_nH_{2n+2} + \left(\frac{3n+1}{2}\right) O_2 \rightarrow nCO_2 + (n+1)\, H_2O \qquad \text{(B-1)}$$

Also, assume that the particulates sampled are composed only of carbon. The mass of fuel burned to produce that mass of carbon is found from a material balance of the assumed equation for its formation,

$$C_nH_{2n+2} + \left(\frac{n+1}{2}\right) O_2 \rightarrow nC + (n+1)H_2O \qquad \text{(B-2)}$$

The EI is calculated by dividing the mass of particulate sampled by the mass of fuel burned and multiplying the ratio by 1,000.

Using the data at sampling point 1, i.e.,

$T = 70°C$, $P = 702$ torr $= 0.924$ atmosphere
0.28 vol % CO_2 in gas sampled
$M_p = 0.0509$ gram particulates collected
$V = 595$ liters of gas sampled

The calculation is as follows

The partial volume of CO_2,

$$V_{CO_2} = (0.0028)(595) \text{ liters} = 1.667 \text{ liters}$$

Using the ideal gas law for partial volumes,

$$V_{CO_2} = \frac{n_{CO_2} RT}{P} = \frac{M_{CO_2}}{44} \frac{RT}{P} \qquad \text{(B-3)}$$

where

P = total pressure of gas = 0.924 atmosphere
T = temperature of gas = 343°K
R = gas constant = 0.0821 atmosphere-liters/gram-mole °K
n_{CO_2} = gram moles of CO_2, and
M_{CO_2} = mass in grams of CO_2

Transposing equation B-3, and substituting the above values, we get M_{CO_2} = 2.40 grams.

From a material balance of equation B-1, the mass of fuel burned to form CO_2 is

$$M_a = \frac{14.2\ M_{CO_2}}{44.0} \qquad \text{(B-4)}$$

if the predominant molecular species in the fuel is $C_{12}H_{26}$.

M_a = 0.773 grams upon substitution of M_{CO_2}.

From a material balance of equation B-2, the mass of fuel burned to form carbon is

$$M_a = \frac{14.2}{12.0}\ Mp \qquad \text{(B-5)}$$

M_b = 0.0601 grams upon substitution of Mp. The total fuel consumed to form CO_2 and carbon is $M_{fuel} = M_a + M_b$ = 0.833 grams.

The EI

$$EI = \frac{M_p}{M_{fuel}} \times 1{,}000 \qquad \text{(B-6)}$$

is found to be 61.1 upon substitution. Similarily, it is found to be 59.5 and 64.1 at points 2 and 3, respectively.

These calculations assume that the above material balances account for the fuel consumed. They, however, ignore uncondensed hydrocarbon gases. Also, the above calculations neglect entrainment of ambient air. Although, both the particulate and carbon dioxide concentrations are diluted, the ratios of particulate to carbon dioxide or particulate to fuel consumed are decreased due to the 0.03 mole % CO_2 in the entrained ambient air. Thus, EIs will be larger than the above values if dilution by ambient air were to be considered in the calculations.

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